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Modelling shoreline changes at Northwest of Portugal using a process-based numerical model: COAST2D

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Abstract: The coastal stretch between Vagueira and Praia de Mira, northern Portugal, is subject to high-energy wave conditions. At the same time, the shoreline is a main contributor to the local economy, extensively due to tourism. Despite the shoreline is currently protected by groynes, a better understanding on the hydrodynamics and the morphodynamics in the area is crucial for coastal managers and planners. In this work it is intended to use a process-based model, COAST2D, to predict the beach morphological changes of the said sandy beach as the study site. The model is applied to simulate the morphological changes over a 4-month period between October 2013 and February 2014 to the study site, during which a series of high intensity storm events occurred along the west coasts of Europe. Model results are compared with the measurements from topo-bathymetric fieldwork campaigns. The model results show the effect of the groynes on the nearshore coastal processes under the combined wave and tide conditions. The predicted morphological changes agree well with the field measurements. The model results also show the shoreline sensibility at the study site to high-energy waves during storms, where shoreline changed its slope to adapt to the more energetic conditions. The results clearly demonstrate the capability of COAST2D in modelling the complex hydrodynamics and morphodynamics at the study site in a seasonal scale.

Keywords: *sediment transport; groynes; coastal modelling; Vagueira-Praia de Mira; storm event and seasonal scale simulations*

30

31 **1. Introduction**

32 Shoreline is constantly changing due to the action of wind, waves, tides and sea level variations. Coastal
33 erosion and coastal flooding become increasingly severer and more challenging for coastal engineers and
34 coastal zone managers to tackle. In the past decades, various coastal defence structures have been built
35 worldwide to protect coasts and the coastal environment. These structures include sea walls, longitudinal
36 coastal revetments and detached breakwaters, groynes or a combination of those mentioned, in addition to the
37 soft engineering approaches, such as beach nourishment. With global warming due to the climate change,
38 which leads to the sea level rise, the frequency and severity of the storms are expected to increase, and coasts
39 and coastal defences become more vulnerable under the extreme storm conditions.

40

41 To ensure the coastal defence structures to be effectively functional for their design life, it requires the
42 designers to fully understand the impacts of the defence structures on the hydrodynamics and morphodynamics
43 in the surrounding areas, and the response of the shoreline at several time scales. In addition to laboratory
44 experiments to detail the coastal processes for various coastal structures (Kramer et al., 2009; Faraci et al.
45 2014; Faraci, 2018), process-based numerical models have been widely used to describe the complex
46 interaction between waves, tides and sediment transport, where coastal defence structures are present, and the
47 resulting morphological and shoreline changes. This approach can be successfully applied for short-term
48 (hours to days) and medium-term (weeks to months) forecasting, such as single or multiple storm events, often
49 at a limited spatial scale associated with specific engineering schemes (Karunarathna et al., 2016). Examples
50 of such models include the applications of XBeach to several sites for morphological evolutions (Roelvink et
51 al., 2009; McCall et al., 2010; Roelvink et al, 2018), and the statistical-process based approach for beach
52 profiles (Pender and Karunarathna, 2013). For the predictions over a longer time and space scales, hybrid
53 modelling, also termed behaviour-oriented models have been used as are the cases of the 1- or N-line shoreline
54 evolution models (Pelnard-Considere, 1956; Hansen and Kraus, 1989; Dabees and Kamphuis, 1998; Hanson et
55 al, 2003; Baptista et al., 2013 and Coelho et al., 2013) and the cross-shore profile evolution models of Stive
56 and de Vriend (1995), Niedoroda et al. (2001) and Larson et al. (2016). In the latter approach, the models retain
57 some elements of the physics in order to reduce computational costs and simplify the dynamics on the

58 assumption that the broad scale morphological changes will be captured (Karunarathna and Reeve, 2013).
59 More recently a new class of approach is the data-driven models in which the measurements of past conditions
60 at a site, together with sophisticated statistical techniques, identify patterns of behaviour that are then
61 extrapolated into the future to form a forecast (Reeve et al., 2016). Despite the potentialities of the new class
62 of models, process based models continue to represent strong tools of prediction due to its capacity of providing
63 valuable insights into complex processes, thus improving the level of understanding of those processes (Reeve
64 et al., 2016). Although the processed-based models are often computationally expensive and also require
65 extensive calibration and validation to ensure the accuracy and effectiveness, once validated, they are capable
66 of providing the detailed interactive processes between hydrodynamics, morphodynamics and structures. The
67 process-based models developed for the past thirty years, have mainly been focused on two-dimensional, depth
68 averaged (2DH) schemes (Fleming and Hunt, 1976; Latteux, 1980; Coeffe and Pechon, 1982, among others).
69 Nicholson et al. (1997) categorize the process-based models according to the manner in which the suspended
70 component of the sediment transport is handled. Some models are based on the assumption that the suspended
71 sediment load is a function of the local conditions only, the resulting potential (or equilibrium) transport rates
72 being described by empirical or semi-empirical expressions (suitable for coarser sediments). Other models
73 solve the time-dependent diffusion-advection equation for the suspended sediment concentrations to yield the
74 dynamic sediment load (suitable for finer sediments). Process-based models have been used to simulate the
75 features associated to offshore breakwaters in micro-tidal conditions (Nicholson et al., 1997); to forecast the
76 behaviour of sandy beaches including outer and inner bars (van Rijn et al., 2003); to predict the complex
77 processes associated with tidal inlets (Roelvink, 2006); to evaluate the generic effect of shore-parallel
78 breakwaters in macro-tidal conditions (Pan et al., 2010). The application of the process-based models to
79 simulate the behaviour of coasts with groyne fields exposed to high energetic wave regimes including extreme
80 events have been less studied. In the present work, an existing process-based morphological model:
81 COAST2D, which has been developed and refined in a number of research projects including the assessment
82 of the impacts that some types of coastal structures produce on the nearshore morphodynamics is adopted.
83 COAST2D was used to model nearshore morphodynamics behind a set of shore-parallel breakwater at Sea
84 Palling, UK (Pan et al., 2005; Du et al., 2010) or a set of V-shaped breakwaters (Pan et al., 2013). COAST2D
85 has been also used in assessing the behaviour of beach nourishment on a costal defence scheme under macro-

86 tide conditions (Pan, 2011), as well as providing data to study morphological changes with statistical approach
87 (Alvarez and Pan, 2016).

88

89 The aim of this work is to simulate the hydrodynamics and morphodynamics of a sandy beach, protected by a
90 set of groynes, of a 9 km section exposed to the high energetic wave regimes present in the Portuguese
91 Northwest coast (Vagueira-Praia de Mira case study) over a 4-month storm period, from October 2013 to
92 February 2014. Field work data include the reference situations with topo-bathymetric surveys carried out at
93 the beginning and the end of study period respectively. The model results are then compared with data obtained
94 in the field. Specifically, the model predicts waves, currents and sediment transport rates under a period from
95 October 2013 to February 2014, which included calm periods and storm conditions for events with
96 approximately one-year return period and 50-year return period, to study nearshore morphological changes
97 and the patterns of erosion and accretion in the study area at the end of the simulation period.

98

99 **2. Site Description**

100 This study focuses on a site located in the Vagueira-Praia de Mira coastal stretch, northern Portugal, as shown
101 in Figure 1, located at some 80 km south to Leixões. Overall, this section of the coast consists of the Aveiro
102 Harbour in the north and Praia de Mira beach in the south. In between, there are a group of 5 groynes at Costa
103 Nova and several longitudinal revetments, and two groynes at Vagueira and Labrego together with a
104 longitudinal revetment at Vagueira. The most recent groynes were built in 2002/2003 at Areão and Poço da
105 Cruz (Costa and Coelho, 2013).

106

107 This site was particularly chosen because of the complex hydro-morphodynamics due to the presence of the
108 coastal structures, as well as the availability of the field data. The Vagueira-Mira coastal stretch, located at the
109 Northwest coast of Portugal, is a sand barrier that separates the Aveiro lagoon from the ocean. This sandy
110 coastal system is under a very energetic wave climate, where major storms are from the Northwest quadrant,
111 being swell-dominated with the main wave direction in WNW-NNW (Coelho and Veloso-Gomes, 2003;
112 Coelho *et al.*, 2009). As a consequence of the wave climate, littoral drift currents also act mainly in North-
113 South direction which has been clearly evidenced by accretion areas located at north of groins and erosion

114 areas at the south (Dias *et al.*, 2014). Thus, this coastal stretch experiences severe erosion problems,
115 particularly in the area between the Costa Nova and Mira beaches, which is located about 20 km south of the
116 Aveiro harbour breakwater (Figure 1).

Figure 1 Location of the extended study area, northern Portugal.

118
119 Stated in Vitorino et al. (2002), during June and September, significant wave heights and mean periods in this
120 region are consistently less than 3 m and 8 s, which can be regarded as relatively calm period. In other seasons,
121 the mean significant wave heights and periods exceeds 3 m (most frequent values of 3-4 m) and 8 s (most
122 frequent mean periods of 8-9 s). During storms, the mean significant wave heights are frequently greater than
123 5 m and often in exceed of 7 m. The mean wave period is approximately 13 s, with the maximum peak wave
124 period reaching 18 s (Vitorino et al., 2002). The tides in the study site are semidiurnal, with the average spring
125 and neap tidal ranges being 2.8 m and 1.2 m respectively.

126
127 As described in Scott et al. (2016), the winter of 2013/14, which is the period considered in this study, was a
128 rare (approximately 50-year return period) event. The joint Hs-Tp probability of the storm named Hercules
129 (Hs = 9 m; Tp = 23 s) on 6 January 2014 identified it as a 1:5 to 1:10 year wave event based on the data
130 provided by the UK Met Office, in the Portuguese west coast, while the IPMA (Instituto Português do Mar e
131 da Atmosfera) named this event as Christina (Hs = 9 m; Tp = 27 s).

132
133 Figure 2 shows that the close-up of the satellite images of the study area, including both groynes at Areão and
134 Poço da Cruz. Two topo-bathymetric campaigns were carried out, on the 9th October 2013 and 1st February
135 2014, along the stretch of coast between Vagueira and Praia de Mira, as shown in Figure 2. There are two
136 groynes in the surveyed area, which are in a slightly curved configuration against the predominant incoming
137 wave direction, as shown in Figure 2 (inserts).

Figure 2. Satellite images for the study area and the computational domain

140 For the subaerial beach, the topographic surveys were performed with a prototype system (INSHORE)
141 mounted on a four-wheel motor quad, which includes a set of Global Positioning System (GPS) antennae and
142 a laser unit for distance measurement (Baptista et al., 2008; Baptista et al., 2011). The measurements were
143 carried out during low-tide conditions in a dense profile grid, which included alongshore and cross-shore
144 transects (profiles with 50 to 70 m spacing). GPS data were processed using Real-Time Kinematic RTK GPS
145 software (Cunha, 2002) by means of an algorithm for kinematic ambiguity fixing in the two GPS L-bands
146 frequencies L1/L2 (L1= 1572.42 MHz; L2=1227.60 MHz) (Hofmann-Wellenhof et al., 1992). The accuracy
147 of the final Differential GPS (DGPS) positions is within 0.03 m horizontally (x and y) and 0.04 m vertically
148 (z) (Baptista et al., 2011). Ellipsoidal heights were also converted to the national MSL altimetric datum of the
149 Cascais tide gauge. The Triangular Irregular Networks (TIN) method (Lee and Schachter, 1980) was also used
150 to convert data point observations to a 3D surface represented by a detailed DEM contour map (1.0 m of
151 resolution). From the generated DEM, the shoreline position was extracted by considering the contour line of
152 1 m above the Mean Sea Level (Altimetric datum of Cascais tide gauge). For the submersed beach the
153 INSHORE prototype was adapted to a vessel in which the laser unit was replaced by a single beam echo
154 sounder. The survey domain includes the active profile above the -10 m depth. Cross-shore profiles were 500
155 m spaced along the study site.

156

157 Sediment size was also extensively measured in the study area (Silva et al., 2009; Narra et al., 2015), showing
158 a high temporal and spatial variability. Within the present study area, D_{50} ranges from 0.35mm to 0.52mm. It
159 is worth mentioning that the study site is adjacent to the Aveiro Harbour in the north, as shown in Figure 1,
160 the breakwater in the updrift side of the harbour retains part of littoral drift, reducing the sediment supply to
161 the down-drift coast.

162

163 **3. Model Description**

164 The COAST2D model is a 2D depth-averaged hydrodynamic and morphodynamics model, which has been
165 well validated during its development and refinement. The model consists of a number of fully interactive
166 modules, mainly: (1) a wave module to determine wave-period, averaged wave energy or wave height and
167 wave direction for the wave transformation from offshore to nearshore; and a current module to compute the

depth-integrated current velocity and water surface elevation under both tide and wave actions; (2) a morphological module to compute the sediment transport rates using equilibrium formulae, as well as the resulting bed level changes. The model also includes full wave-current and hydrodynamic-morphological interactions. While the further information can be found elsewhere (Pan et al., 2005, 2007; Du et al., 2010), only principal governing equations are briefly given in this paper in the following sections to the aspects of currents, waves and sediment transport.

3.1 Currents

The governing equations for the water surface elevation and 2D depth averaged currents are the continuity and momentum equations, as shown below:

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x}(dU) + \frac{\partial}{\partial y}(dV) = 0 \quad (1)$$

where: z = surface elevation; t = time; U , V = horizontal depth-integrated velocity components in the x and y directions; and d = water depth.

$$\begin{aligned} \frac{\partial dU}{\partial t} + \frac{\partial dUU}{\partial x} + \frac{\partial dUV}{\partial y} - \frac{\partial}{\partial x}\left(v \frac{\partial dU}{\partial x}\right) - \frac{\partial}{\partial y}\left(v \frac{\partial dU}{\partial y}\right) + \\ gd \frac{\partial z}{\partial x} + C_x U \sqrt{U^2 + V^2} + fdV - \frac{1}{\rho} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \tau_{wx} = 0 \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial dV}{\partial t} + \frac{\partial dVU}{\partial x} + \frac{\partial dVV}{\partial y} - \frac{\partial}{\partial x}\left(v \frac{\partial dV}{\partial x}\right) - \frac{\partial}{\partial y}\left(v \frac{\partial dV}{\partial y}\right) + \\ gd \frac{\partial z}{\partial y} + C_y V \sqrt{U^2 + V^2} - fdU + \frac{1}{\rho} \left(\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) + \tau_{wy} = 0 \end{aligned} \quad (3)$$

where: C_x and C_y = frictional coefficients in x and y directions for U and V respectively; v = turbulent eddy viscosity; f = Coriolis force coefficient; S_{xx} , S_{xy} , S_{yy} = wave radiation stresses if wave computation is coupled (detailed later); τ_{wx} , τ_{wy} = wind shear stresses on the surface. If the bed form effects are not considered, the bed friction is calculated by $C_x = C_y = 0.016(\Delta/d)^{1/3}$, where: Δ = roughness height, which can be related to the sediment size as $\Delta \approx 2.5D_{50}$ and D_{50} is the median grain size.

189 3.2 Waves

190 The two equations describing the wave vectors are derived from the kinematic conservation equation (Phillips,
191 1977):

$$192 \quad \frac{\partial K_i}{\partial t} + \frac{\partial \omega}{\partial x_i} = 0 \quad (4)$$

193 where: K_i = wave number vector $\{i=1,2\}$; t = time; ω = apparent wave frequency; and x_i = horizontal coordinate
194 vector. To include the effect of currents, it is assumed that the waves are propagating on a medium moving
195 with velocity U_i . The apparent frequency is then given by the Doppler equation: $\omega = \sigma + K_j U_j$, where: σ =
196 intrinsic wave frequency. Applying the small amplitude wave theory, the intrinsic wave frequency can be
197 described by the linear dispersion equation: $\sigma^2 = gk \tanh(kd)$, where: k = wave separation factor.

198
199 Taking account for the wave diffraction based on the approach proposed by Battjes and Janssen (1978), for
200 the effect of wave amplitude on the kinematics of small-amplitude waves, the wave number vectors can be
201 calculated using:

$$202 \quad K_j K_j = k^2 + \frac{1}{A} \nabla^2 A \quad (5)$$

203 where: A = wave amplitude. Differentiating Eq. (5) leads to the following equations for wave directions in
204 both x and y directions respectively:

$$205 \quad \frac{\partial P}{\partial t} + \left[C_g \frac{P}{k} + U \right] \frac{\partial P}{\partial x} + \left[C_g \frac{Q}{k} + V \right] \frac{\partial P}{\partial y} + \frac{\sigma G}{2d} \frac{\partial d}{\partial x} - \frac{C_g}{2k} \frac{\partial \Phi}{\partial x} + P \frac{\partial U}{\partial x} + Q \frac{\partial V}{\partial x} = 0 \quad (6)$$

$$206 \quad \frac{\partial Q}{\partial t} + \left[C_g \frac{P}{k} + U \right] \frac{\partial Q}{\partial x} + \left[C_g \frac{Q}{k} + V \right] \frac{\partial Q}{\partial y} + \frac{\sigma G}{2d} \frac{\partial d}{\partial y} - \frac{C_g}{2k} \frac{\partial \Phi}{\partial y} + P \frac{\partial U}{\partial y} + Q \frac{\partial V}{\partial y} = 0 \quad (7)$$

207 where: P, Q = wave number vectors in x and y directions; $\Phi = \frac{1}{A} \nabla^2 A$; wave group velocity $C_g = \frac{\sigma}{2k} (1 + G)$

208 ; and $G = \frac{2kd}{\sinh(2kd)}$.

209

210 For wave amplitude, the energy conservation equation for small-amplitude and linear waves in a moving
211 medium is used as (Phillips, 1977):

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_i} (EU_i + F_i) + S_{ij} \frac{\partial U_j}{\partial x_i} + \tilde{D} = 0 \quad (8)$$

where: E = total wave energy; F_i = wave flux vector; S_{ij} = radiation stress tensor $\{i=1,2\}$; and \tilde{D} = energy dissipation due to the wave breaking and the bottom friction. Considering the relation between wave amplitude and wave energy gives the following equation:

$$\begin{aligned} \frac{\partial A}{\partial t} + \frac{1}{2A} \left\{ \frac{\partial}{\partial x} \left[A^2 \left(\frac{C_g}{k} P + U \right) \right] + \frac{\partial}{\partial y} \left[A^2 \left(\frac{C_g}{k} Q + V \right) \right] \right\} \\ + \frac{1}{\rho g A} \left[S_{xx} \frac{\partial U}{\partial x} + S_{xy} \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) + S_{yy} \frac{\partial V}{\partial y} \right] + C_a A = 0 \end{aligned} \quad (9)$$

where: C_a = dissipation coefficient due to the wave breaking and the bottom friction; and S_{xx} , S_{xy} , S_{yy} = wave radiation stresses given by:

$$S_{ij} = \frac{1}{2} \left[(1 + G) \frac{K_i K_j}{k^2} + G \delta_{ij} \right] E \quad (10)$$

For random waves, the energy dissipation due wave breaking is considered with the approach proposed by Battjes and Janssen (1978), which can be calculated using: $\tilde{D} = \frac{\alpha \pi}{2T} Q_b H_m^2$, where: H_m = the maximum possible wave height; Q_b = the probability of wave breaking; and α = constant.

3.3 Sediment transport

The total sediment transport which includes both bed load and suspended sediment transport for combined waves and current conditions, as suggested by Soulsby (1998), is used in the model:

$$q_t = A_s U \left[\left(U^2 + \frac{0.018}{C_D} U_{rms}^2 \right)^{1/2} - U_{cr} \right]^{2.4} (1 - 1.6 \tan \beta) \quad (11)$$

where:

$$A_{sb} = \frac{0.005 h (d_{50}/h)^{1.2}}{[(s-1)g d_{50}]^{1.2}} \quad (12)$$

$$A_{ss} = \frac{0.012 d_{50} D_*^{-0.6}}{[(s-1)g d_{50}]^{1.2}} \quad (13)$$

$$A_s = A_{sb} + A_{ss} \quad (14)$$

$$C_D = \left[\frac{0.40}{\ln(h/z_0) - 1} \right]^2 \quad (15)$$

and, q_t = the volumetric transport rate; D^* = dimensionless grain diameter; C_D = drag coefficient due to current alone; β = slope of bed in stream wise direction, positive if flow runs uphill; \bar{U} = depth-averaged current velocity; U_{rms} = root-mean-square wave orbital velocity; and z_0 = roughness height. For rippled bed, z_0 is set to 6 mm.

All governing equations described above are discretised and solved using explicit finite difference methods with appropriate boundary conditions specified. All modules are fully and dynamically interacted between both hydrodynamics and morphodynamics.

4. Model Setup

In this study, the main focused modelling area is the central part of the coast between Vagueira and Praia de Mira. To drive the model, offshore wave data measured from a wave station at Leixões, located some 80km at north of Aveiro, is available for this study. Figure 3 shows the measured wave height time series at Leixões, wave directions and the correlation of wave height and wave period. Incident waves are predominately from North-west direction and the wave periods range from 5 to 15 seconds with a clear correlation with the significant wave height. The circles in Figure 3 (a and b) indicate the dates of the topo-bathymetric surveys.

Figure 3. Offshore wave conditions: (a) significant wave height (H_s); (b) wave direction; and (c) correlation between significant wave height and wave period at Leixões station (October 2013 to February 2014).

As the focus of this study is to investigate the beach morphological changes with the presence of groynes at Areão and Poço da Cruz using the fine resolution COAST2D model, it becomes necessary to carry out the modelling in two stages. The first stage is to set up COAST2D over a larger computational domain, extending from the wave buoy station at Leixões to the nearshore area with a coarser grid for simulating hydrodynamics only. The main purpose of this exercise is to transform that wave conditions measured at the wave buoy station

257 to the open boundary of the smaller, but fine resolution COAST2D setup, for the coastal morphological
258 simulations. The computational domain for a coarser grid is shown in Figure 4, which covers an area of 120
259 km in the alongshore direction and 40 km in the across-shore direction, with the respective 1 km and 0.4 km
260 grid sizes. The COAST2D model is run over a period of 2760 hours, generating the wave conditions at location
261 A, for the fine grid model at the second stage.

262

263

Figure 4. The computational domains of the COAST2D setups for the two stage simulations (finer-resolution domain is indicated as A).

264

265 The computed wave heights generated by COAST2D at location A for a time period between 9th October 2013
266 (t=0h) to 1st February 2014 (t=2760h) are compared with the measured ones at Leixões wave buoy in Figure
267 5, during which, three storm events occurred as indicated by the grey bands (see also Table 1).

268

Figure 5. The wave heights generated by COAST2D at Location A, in comparison with the measured ones. Storm events are indicated by the grey bands.

269

270 At stage two, the fine resolution COAST2D model was then set to cover the computational area of 9 km in the
271 alongshore direction and 2.565 km in the cross-shore direction, as shown in Figure 6, with the inclusion of
272 groynes at Areão and Poço da Cruz. The computational grid consists of 361 by 172 node points with grid sizes
273 of 25m in the longshore direction and 15m in the cross-shore direction. A finer grid size is used in the cross-
274 shore direction to increase the resolution to better capture the hydrodynamic and morphodynamic variations
275 and to better present the curvature of the groynes. Bathymetry data surveyed on 9th October 2013 is interpolated
276 as the initial bathymetry for the model, as shown in Figure 6. The water depth along the offshore (open)
277 boundary is approximately 16 m. The model is forced by the wave and tide conditions based on the field
278 measurements which are described in detail in the following sections.

279

Figure 6. Finer-resolution COAST2D computational domain and the locations of Box A (covering Poço da Cruz Groyne); Box B (covering Areão Groyne) and Box C (covering the nearshore area as shown).

280

281 Along the offshore boundary, time varying wave conditions (wave height, period and direction) are specified
282 in 0.5 hourly intervals, based on the measurements obtained at the Leixões station, following the first stage
283 simulations, as described previously. In this study, an M2 semidiurnal tide with a 2 m tidal range is used along
284 the offshore boundary of the computational domain, as the representative tides at the study site. Despite the
285 high temporal and spatial variability of the sediment size presented by Silva et al. (2009), sediment with an
286 average D_{50} of 0.45 mm is used for the entire domain. Groynes are treated as bathymetry with increased
287 roughness, but non-erodible, although sediment deposition on groynes is allowed. The crest level of the
288 groynes is set to 4 m and their curvature is approximated well within the computational grid.

289

290 To facilitate the analysis of the impact the groynes have on the nearshore morphodynamics, three boxes were
291 defined within the computational domain, as illustrated in Figure 6. Boxes A and B are centred at both groynes,
292 expanding 500 m each way alongshore and 600m across-shore, from the berm to offshore. Box A is centred at
293 Poço da Cruz Groyne and Box B is centred at Areão Groyne, while Box C covers the central part of the
294 nearshore beach.

295

296 **5. Results and discussion**

297 Using the wave and tide conditions described in the previous sections, the COAST2D model is applied to the
298 study site to stimulate the beach morphological changes over a period of about 4 months (2760 hours),
299 corresponding to the period from the 9th October 2013 to 1st February 2014. The morphological changes along
300 the simulated time, as well as the predicted waves and sediment transport from the model are examined in the
301 predefined boxes A (Poço da Cruz Groyne) and B (Areão Groyne) as shown in Figure 6.

302

303 Additionally, three storm events have been defined within the 2760-hour period simulated (Table 1). Results
304 are analysed for each of the storms to facilitate understanding how the shoreline reacts to each of the storm
305 events. For the study area, the mean significant wave height is around 2 m (Narra et al., 2015), although during
306 storms, wave height can reach 8 m (Costa et al., 2001). Commonly, storms last for less than 2 days. However,

307 storms that persist for up to 5 days were already registered (Costa et al., 2001). For a storm defined as a wave
308 field with significant wave heights greater than 3 m, the average storm duration is 60 hours (Sancho et al.,
309 2016).

310

311 Table 1. Storm events definition, in accordance with the simulation period (see also Figure 5).

312

313 Figure 7 shows the volumetric changes of evolution for each box around the groynes during the study period.
314 It should be noted that the volumetric changes for Box C have been scaled by 10 for the sake of clarity. Overall,
315 results show that volume increases over the observed period, which represent general accretion. During storm
316 1 ($250\text{h} < t < 810\text{h}$), two different behaviours can be identified. Before $t=500\text{h}$, the maximum wave height
317 reached a value of nearly 6 m (mean significant wave height of 3.6 m for the period $250\text{h} < t < 500\text{h}$), enter
318 in the domain and accretion occur at similar rates in both boxes. After $t=500\text{h}$ wave height decrease (mean
319 significant wave height of 1.8 m for the period $500\text{h} < t < 810\text{h}$). At this time, volumetric changes increase
320 significantly in Box B (for Areão Groyne) remaining nearly constant for Box A (for Poço da Cruz Groyne).
321 This may suggest that most of the sediments transported by longshore drift currents was trapped in the up-drift
322 groyne (Box B) which in turns facilitates some down-drift erosion, as seen after $t=500\text{h}$ in box A (Poço da
323 Cruz), preventing sediment to reach Box A. It must be highlighted that the main wave direction during this
324 first storm was from WNW (wave direction of 308° for the period $250\text{h} < t < 500\text{h}$ and wave direction of 310°
325 for the period $500\text{h} < t < 810\text{h}$). During the following 690h (810h to 1500h) waves gradually reduce their
326 height and volumetric changes remain nearly constant. When the second storm reaches the domain, around
327 $t=1500\text{h}$, both boxes react very similarly in terms of volumetric changes during the time period between 1500h
328 $< t < 1900\text{h}$, highlighting however the fact that the box A present a consistent lower volume. Once again the
329 wave direction during the second storm was from WNW. At $t=1900\text{h}$ it can be seen how Box B, located updrift,
330 reduce its volume (slight erosion). The period of time between 1900h and 1948h correspond to the storm 2
331 peak (significant wave height of 6.2 m and mean wave direction of 320° - NW). The change of the wave
332 direction to a northernmost position may be the main factor to induce sediment transport previous trapped in
333 box B to box A, since longshore drift currents should be enhanced. This sediment is placed in Box A hours
334 later, as it can be seen a sudden small peak in the volumetric changes for Box A, right after $t=2000\text{h}$. Around

335 t=2250h, the system reacts in an opposite way. Box B, located updrift, seems to be trapping the sediment
336 therefore increasing its volume, while box A reduces slightly, as sediment is trapped upstream. A decrease of
337 wave height (2.5 m) and wave direction (299°) may be the main factors to induce this behaviour. The last storm
338 affects both boxes similarly. As shown by the volumetric changes in Box C, the combined effect reaffirms the
339 results for the individual box.

340

Figure 7. Time series of volumetric changes within Box A (red), Box B (green) and Box C (blue).

341

342 Figure 8 shows the daily average volumetric changes at each box for each of the storms. These results should
343 be analysed in terms of the severity of storm events and the associate mean wave direction. During the study
344 period storm events from WNW direction (Storms 1 and 3) induce up-drift sediment retention (Box B – Areão
345 Groyne) that promotes lower sedimentary retention in Box A. As higher is the value of significant wave height
346 the higher is the volume trapped in the boxes. The storm event from NW direction (Storm 2) induces an up-
347 drift sedimentary transport (Box B) which is down-drift trapped (Box A). This is due to the erosion suffered
348 by Box B before t=2000h, moving sediments from Box B to Box A. Nevertheless, overall, Box B suffers more
349 changes than A, which shows how the down-drift groyne area (Box A for Poço da Cruz) benefit from the
350 protection provided by the northern groyne (Box B for Areão) which regulates the deposition and accretion
351 downstream. Overall volumetric changes in the nearshore area, as shown in Box C, indicates a progressive
352 accretion from three storm events.

353

Figure 8. Daily average volumetric changes in each box for 3 storm events.

354

355 The volumetric changes in the nearshore area (in Box C) during the simulation period, as shown in Figure 8,
356 indicate the overall accretive nature of this coastal stretch of the coast for the storm events.

357

358 Figure 9 shows the spatial distribution of the measured and modelled morphological changes during the 2760h-
359 period studied for a nearshore area extracted from the computational domain indicated in Figure 6. It can be
360 seen that the model represents well the changes occurred within the domain. The erosion and accretion areas

361 are well represented. It can be seen how major erosion affects the shoreline area updrift each groyne while
362 erosion is limited or even turned into accretion downdrift the groynes. In general, deposition occur all over the
363 more offshore area, which indicates the shoreline is shifting to a more gentle slope becoming a dissipative
364 profile, as a reaction to the high energy wave climate.

365

Figure 9. Comparison of measured and computed morphological changes (white lines indicating the locations of groynes, and colour indicates state of morphological changes: erosion (-1), accretion (1) and no changes (0)).

366

367 Figure 10 shows the wave height distribution and modelled bathymetry for each of the boxes A and B, and for
368 the first and last of the storms defined previously. Storm 1 has been characterized for $t=456h$ (27 October
369 2014) and storm 3 for $t=2430h$ (22 January 2015), both corresponding to the highest wave height registered
370 for each of the storms. It must be highlight that $t=456h$ is integrated in the period of first storm ($250h < t <$
371 $500h$) in which the mean significant wave height is of 3.6 m and the main wave direction is from WNW
372 (accretion occur at similar rates in both boxes according to Figure 7); and $t= 2430h$ is integrated in the third
373 storm in which the mean significant wave height is of 3.9 m and the main wave direction is from WNW
374 (accretion also occur at similar rates in both boxes according to Figure 7).

375

376 The wave height for Box A (Poço da Cruz) is shown in Figures 10a (Storm 1) and 10b (Storm 3). In both cases
377 it can be seen how waves are being refracted by the groyne effects on the bathymetry, while quickly reducing
378 their height. It also can be seen how the wave height isolines are nearly parallel to the initial coast (Storm 1),
379 as a result of a smoother bathymetry, but after four months of very energetic wave conditions the bathymetry
380 is rougher. In fact, the regular bathymetry shown in Figure 10a is not verified any more in Figure 10b. This
381 behaviour is also seen for Box B in Figures 10c and 10d. It also can be seen in Figure 10b how the shoreline
382 is levelled at either side of the groyne, meaning there is not significantly more erosion or accretion on each
383 side.

384

Figure 10. Computed wave heights near Poço da Cruz Groyne (Box A) and Areão Groyne (Box B) during Storm 1 ($t=456h$; $H_s=2.3$ m; $T_p = 14$ s; $Dir = 322^\circ$) and Storm 3 ($t=2430h$; $H_s =4.4m$; $T_p = 15$ s; $Dir = 314^\circ$).

The wave height for Box B (Areão) is shown in Figures 10c (Storm 1) and 10d (Storm 3). It is remarkable how in Figure 10d the shoreline is not levelled at either side of the groyne and significant more deposition can be seen updrift of the groyne. This is due to the Areão groyne, updrift retaining a big amount of sediment to travel south towards Box A (Poço da Cruz), explaining the reduced volumetric changes in that area. The wave direction from NW (314°) can also help to justify this behaviour.

Figure 11 shows the sediment transport rates for each box during Storms 1 and 3 at the same time instants as used previously ($t=456h$ and $t=2430h$).

Figure 11. Computed sediment transport rates near Poço da Cruz Groyne (Box A) and Areão Groyne (Box B) during Storm 1 ($t=456h$; $H_s=2.3$ m; $T_p = 14$ s; $Dir = 322^\circ$) and Storm 3 ($t=2430h$; $H_s =4.4m$; $T_p = 15$ s; $Dir = 314^\circ$).

For Poço da Cruz groyne, located at downdrift of the study area, Figure 11a (Storm 1; $H_s=2.3m$) shows a very regular pattern and relatively low sediment transport rates, when compared with Storm 3 as shown in Figure 11b ($H_s=4.4$ m). This behavior can be easily explained by the lower wave heights and consequent lower sediment transport capacity for the Storm 1 instant represented. However, the impact of the groyne in the sediment transport characteristics is similar and near the groyne head the sediment transport rates are higher in both instants, with slightly onshore direction on the updrift side of the groyne and offshore sediment transport movements at downdrift.

At Areão Groyne, the sediments transport rates as shown in Figures 11c and 11d, present also lower values and regular patterns for Storm 1 (lower wave heights). At Storm 3, higher transport rates are observed for bigger depths due to the higher wave heights, which is in correlation with the wider sediment transport patterns of more energetic wave climates. It is also observed an extension of shore where the sediment transport rates are lower, just downdrift the groyne.

409

410 **6. Conclusions**

411 A process-based numerical model, COAST2D, has been used to model the shoreline changes over a 4-month
412 period under the combined wave and tide conditions with the presence of two groynes along the coast in
413 Vagueira-Praia de Mira, northwest of Portugal. During the 4-month simulation period, there were a number of
414 storms including some highly energetic ones, which were measured predominately from the north-west
415 direction. The model results show a general shift in the beach slope towards a gentler and reflective slope. It
416 has been seen how the updrift groyne regulates the amount of sediment reaching the downdrift area, reducing
417 the morphological transport in the sheltered area.

418

419 Qualitatively, the computed final morphological changes from the COAST2D model agrees well with the
420 measured data and the accretion/erosion patterns within the domain are well predicted, which clearly indicate
421 the ability of the COAST2D model in predicting the beach morphological changes under storm conditions.
422 Further sensitivity analysis and comparison of shoreline change may reveal its spatial variability and accuracy
423 of the model. Nevertheless, the results clearly highlight the dynamism in the study site, which results in high
424 volume changes across the domain and a shift in the slope in just a 4-month storm period, and hence, the
425 importance of accurately predicting the coastal erosion for coastal engineers and managers to better assess the
426 effectiveness of future coastal defence schemes.

427

428 The model results can be further improved by including the dynamic temporal and spatial variability of the
429 sediment size, which was found in the study site.

430

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545

546

547

548 TABLE LIST

549

550 Table 1. Storm events definition, in accordance with the simulation period (see also Figure 5).

Storm	1	2	3
Start time (h)	250	1585	2390
Finish time(h)	810	2035	2490
Duration (h)	560	450	100
Duration (days)	23.33	18.75	4.17

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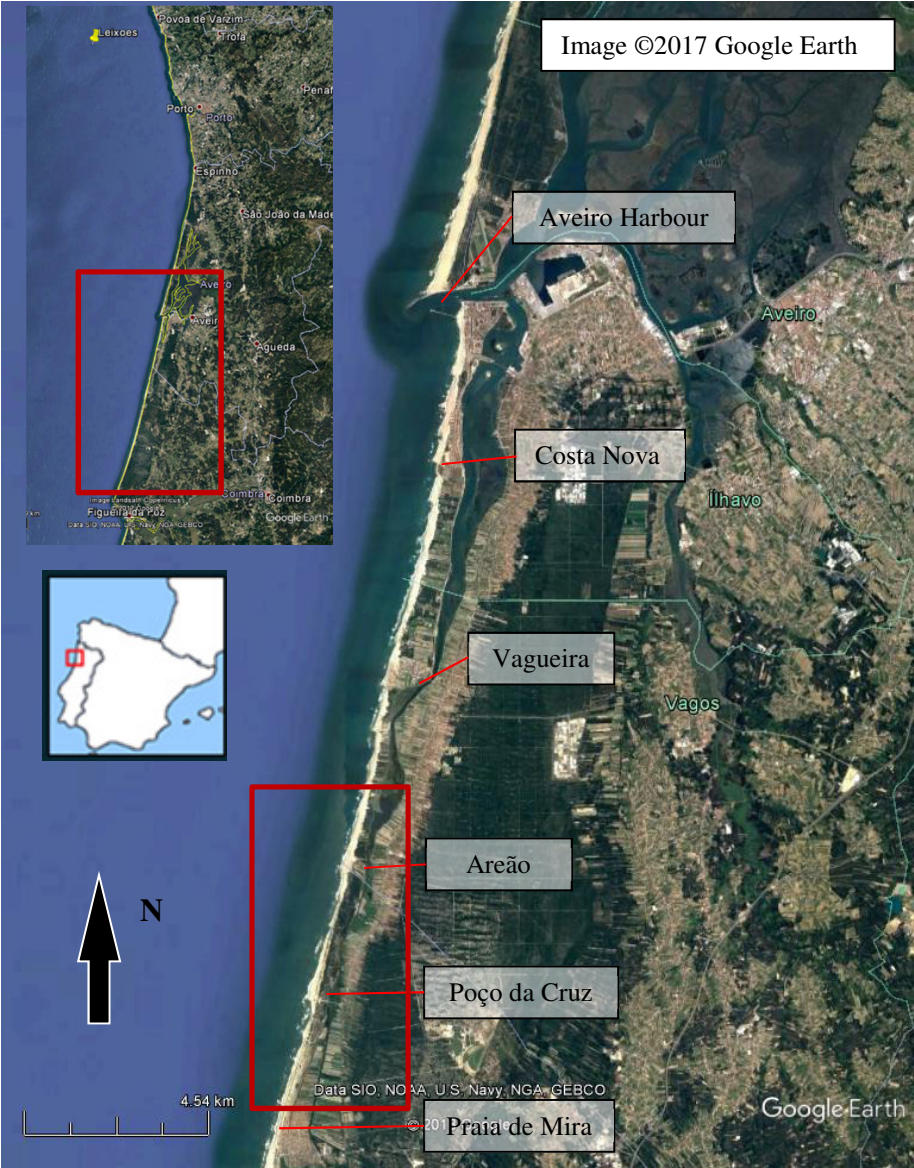
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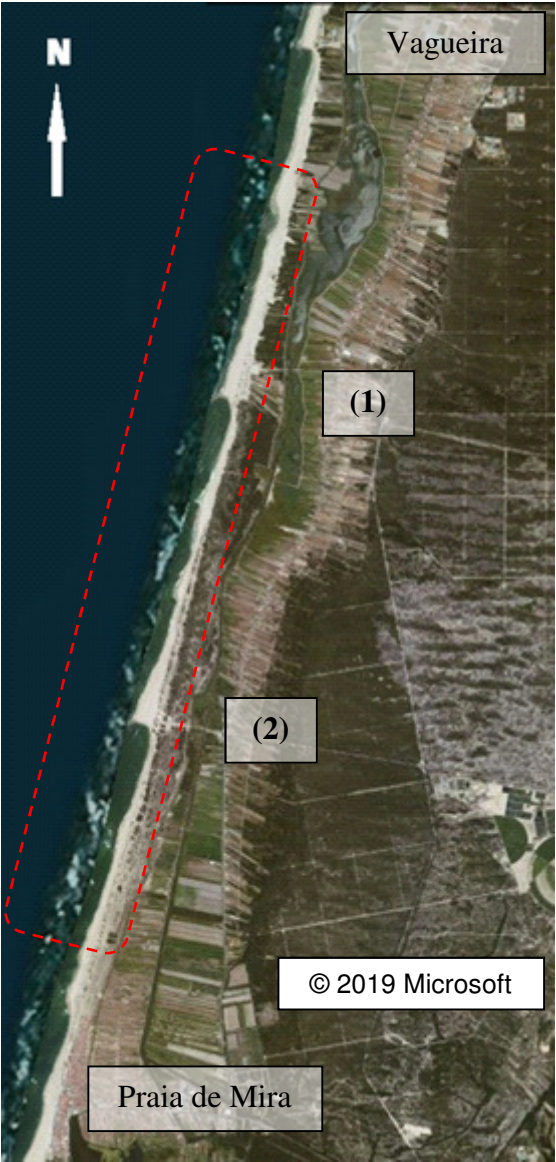
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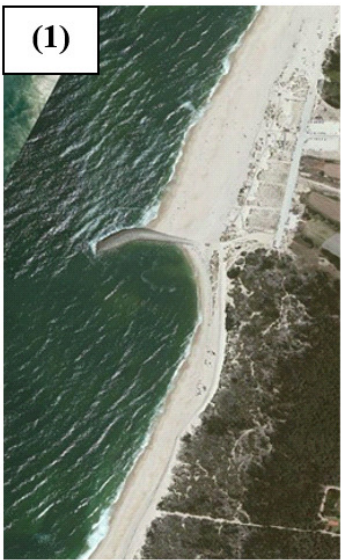
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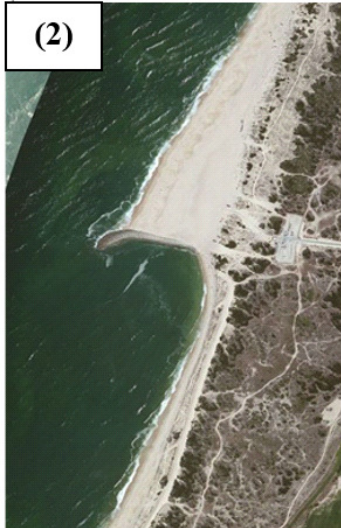




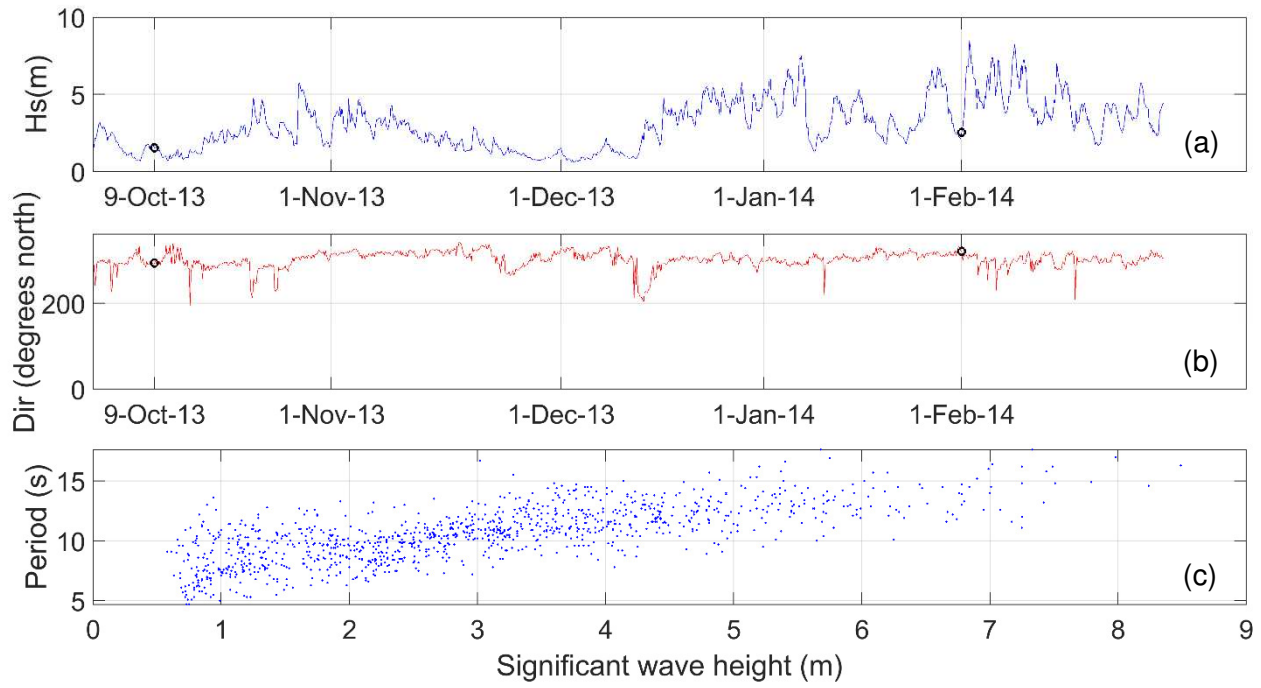
Study site and the computational domain (as boxed).

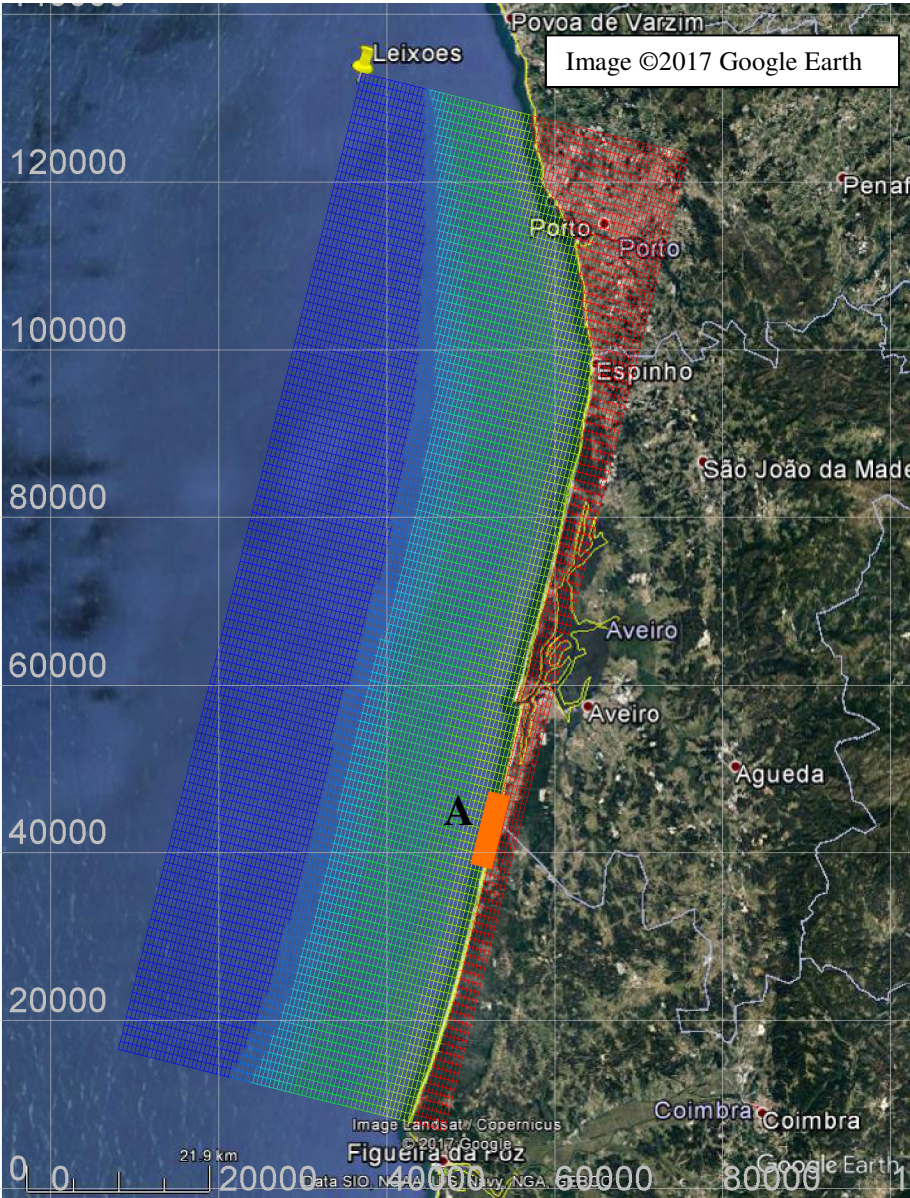


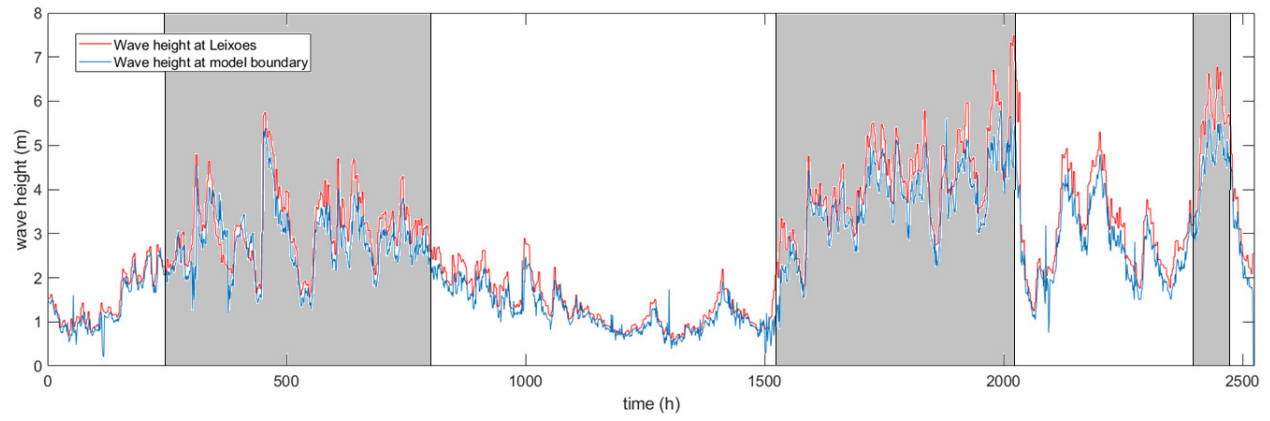
Groyne at Aerão (1)



Groyne at Poço da Cruz (2)







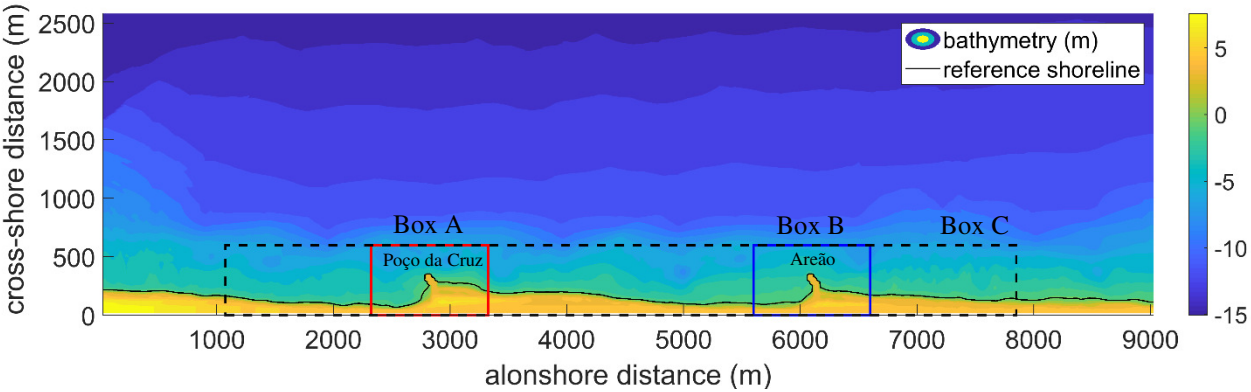
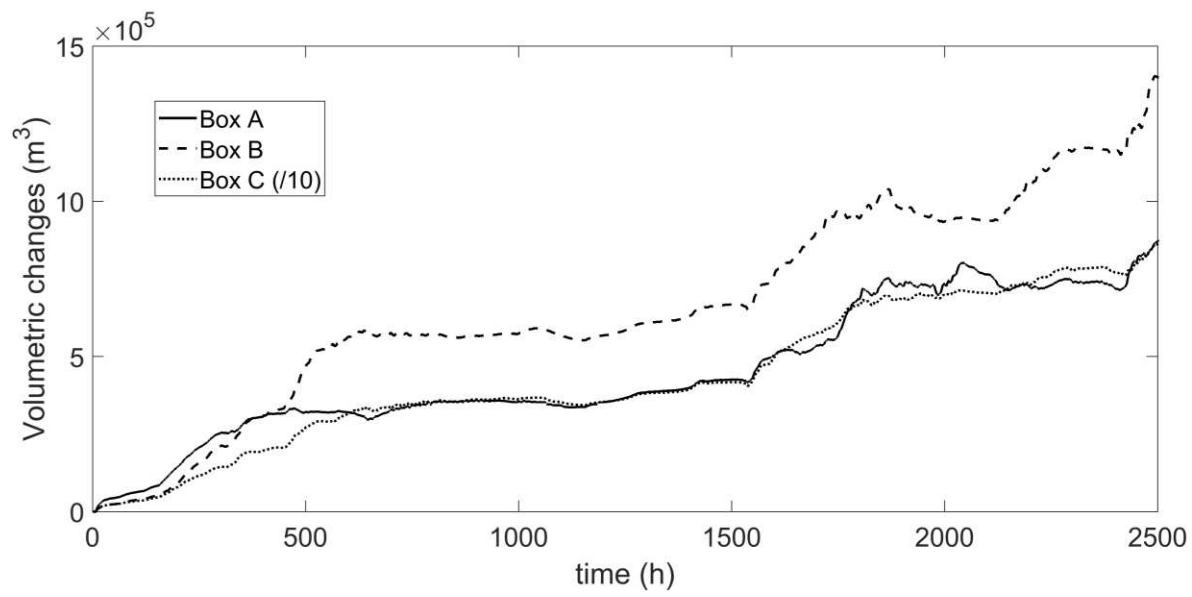
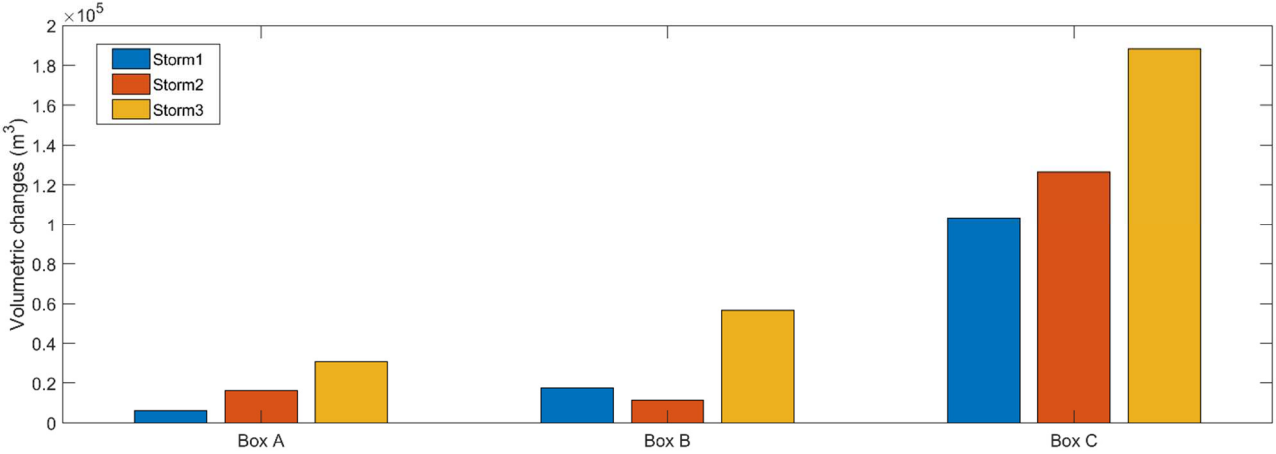
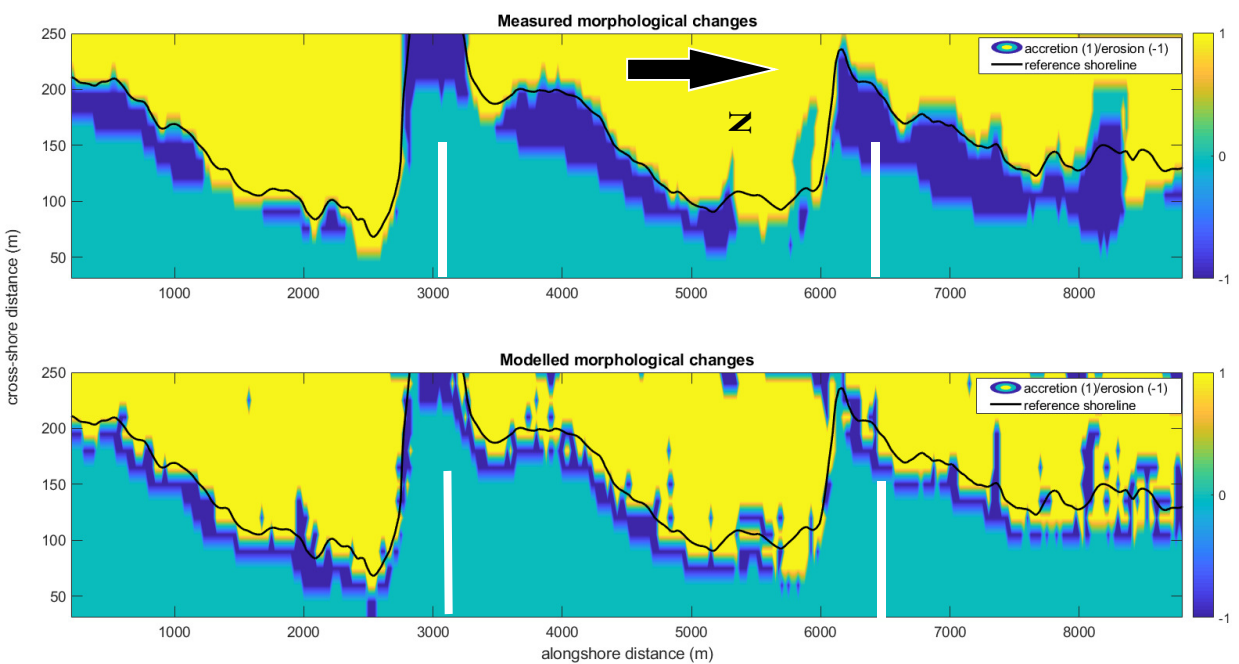
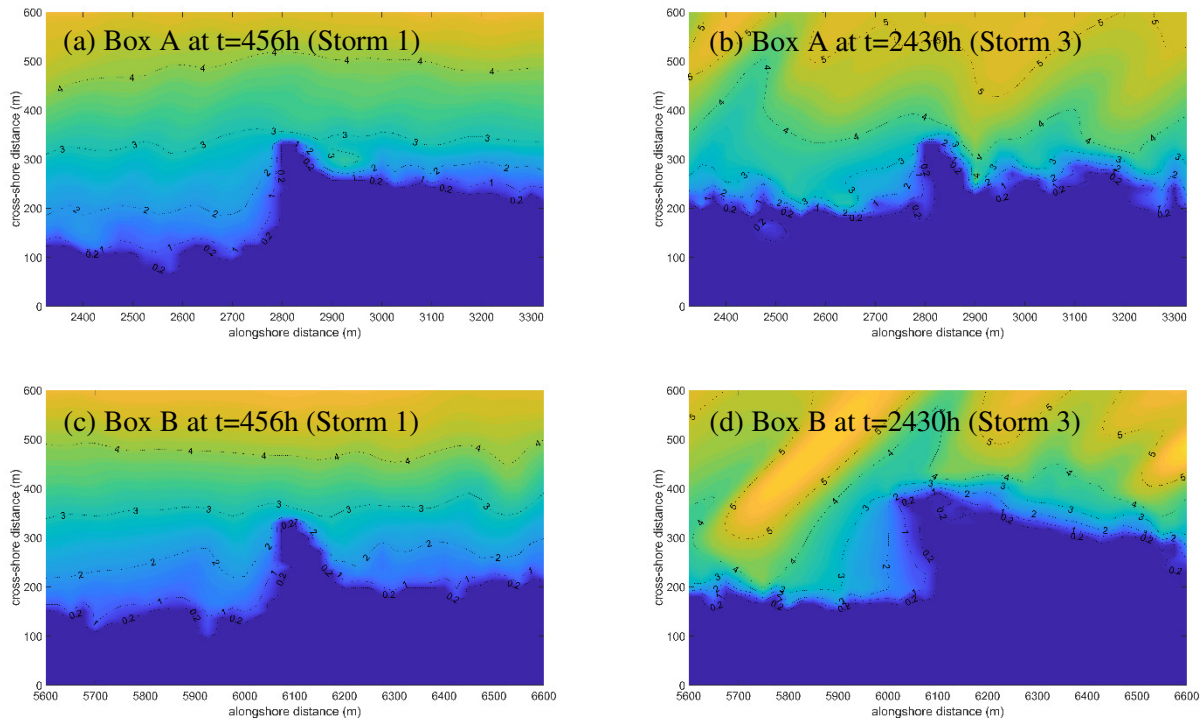


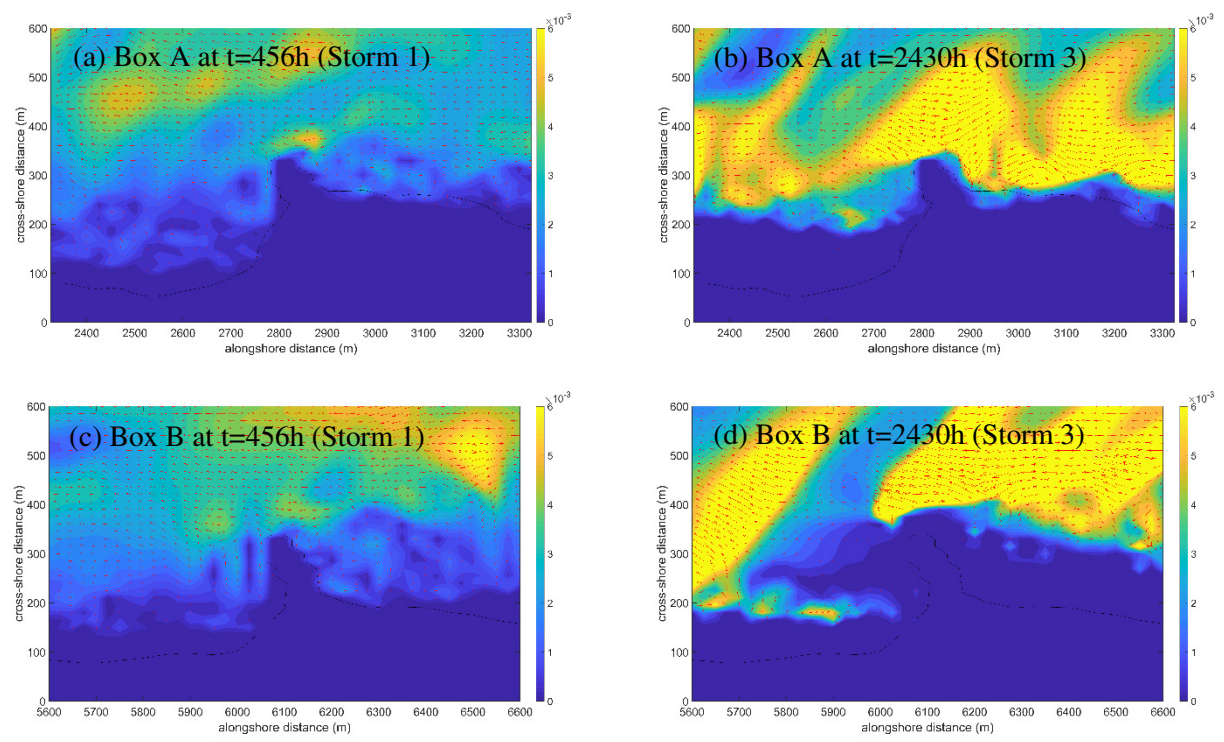
Figure 7



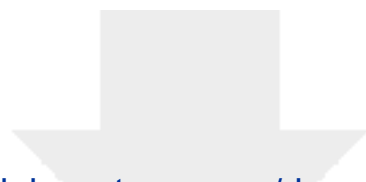








- 1 FIGURE LIST
- 2
- 3 Figure 1 Location of the extended study area, northern Portugal.
- 4 Figure 2. Satellite images for the study area and the computational domain.
- 5 Figure 3. Offshore wave conditions: (a) significant wave height (H_s); (b) wave direction; and (c) correlation
- 6 between significant wave height and wave period at Leixões station (October 2013 to February
- 7 2014).
- 8 Figure 4. The computational domains of the COAST2D setups for the two stage simulations (finer-resolution
- 9 domain is indicated as A).
- 10 Figure 5. The wave heights generated by COAST2D at Location A, in comparison with the measured ones.
- 11 Storm events are indicated by the grey bands.
- 12 Figure 6. Finer-resolution COAST2D computational domain and the locations of Box A (covering Poço da
- 13 Cruz Groyne); Box B (covering Areão Groyne) and Box C (covering the nearshore area as shown).
- 14 Figure 7. Time series of volumetric changes within Box A (red), Box B (green) and Box C (blue).
- 15 Figure 8. Daily average volumetric changes in each box for 3 storm events.
- 16 Figure 9. Comparison of measured and computed morphological changes (white lines indicating the
- 17 locations of groynes, and colour indicates state of morphological changes: erosion (-1), accretion (1)
- 18 and no changes (0)).
- 19 Figure 10. Computed wave heights near Poço da Cruz Groyne (Box A) and Areão Groyne (Box B) during
- 20 Storm 1 ($t=456h$; $H_s=2.3$ m; $T_p = 14$ s; $Dir = 322^\circ$) and Storm 3 ($t=2430h$; $H_s =4.4m$; $T_p = 15$ s; Dir
- 21 $= 314^\circ$).
- 22 Figure 11. Computed sediment transport rates near Poço da Cruz Groyne (Box A) and Areão Groyne (Box
- 23 B) during Storm 1 ($t=456h$; $H_s=2.3$ m; $T_p = 14$ s; $Dir = 322^\circ$) and Storm 3 ($t=2430h$; $H_s =4.4m$; T_p
- 24 $= 15$ s; $Dir = 314^\circ$).
- 25



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